

Optimization of the UMTS Network Radio Coverage On-board an Aircraft

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Abstract—In a world where mobile connectivity has become a need, aircraft passengers still have limited access to communication services during the flight. Both industries and research communities have tried to solve this problem by applying a number of wireless access technologies within the cabin. However, these services are not currently available in commercial aircrafts, where the users have to spend hours isolated from the rest of the world.

The Universal Mobile Terrestrial System (UMTS) has been considered as a candidate wireless access network for providing mobile connectivity. Since UMTS is not a near range technology, it was always assumed that one Node B is enough to cover the whole cabin. However, if only one UMTS Node B is adopted a relatively large transmission power would be required to guarantee an acceptable quality of service. As a consequence, this will interfere with on-board instrumentation and control transmission mechanisms. Moreover some of the signal may radiate outside the cabin possibly interfering with the terrestrial UMTS networks. This type of network topology has the disadvantage of having only one single point of failure and therefore the connection will not be available if the propagation path between the UMTS Node B and the receiving point are obstructed.

This paper tries to solve these problems by applying a number of UMTS Node Bs strategically located around the aircraft, taking a typical configuration of the Airbus A340-600. The optimized network can be derived through simulation where the cabin is modeled as a set of surfaces that form the aircraft fuselage, seats and stowage bins. The dielectric properties of the media, the allowed antenna locations and the antenna patterns were stored in text files and imported in the simulation environment for processing. A number of transmitting antennas are then placed at the available antenna locations and assigned the transmitting power of the UMTS Node B. A three-dimensional ray launching algorithm based on geometric optics (GO) was adopted to derive the propagation paths of the rays launched by the transmitting antenna. A ray sent out by the transmitter travels in free space until it impinges on a

surface. The impinged point is then used to transmit one or two rays, whose directions are derived according to Fermat's principle while the transmitting power of each ray are derived by multiplying the power of the impinged ray to Fresnel's reflection and transmission coefficients. This process goes on for each ray until the propagation power of all the launched, reflected and refracted rays are below a certain threshold.

This process is repeated several times, each time deriving the coverage obtained by the considered network topology. Once an acceptable number of iterations are computed, the topology which provides the best compromise between the number of Node Bs and transmission power levels is selected. The low transmission power required by the proposed solution ensures that the interference on the aircraft signaling infrastructure is minimal. Moreover, the Node Bs can be connected via point-to-point wireless links and therefore the extra weight incurred is minimal.

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1. INTRODUCTION

The use of personal wireless communication devices has increased drastically during the last years. While wireless access is adequately serviced on the ground, air passengers still have limited access to communication services during the flight. This has pushed the aeronautical industry to seek solutions that enable wireless connectivity during the flight as part of their In-Flight Entertainment (IFE).

This paper investigates the optimization of a Universal Terrestrial System (UMTS) network inside an aircraft. UMTS connectivity during flight would ensure seamless passenger audio-visual and data communication with the

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global networks thus increasing customer satisfaction. The work presented here forms part of the integrated project E-Cab (Electronically enabled cabin and associated logistics for improved passenger service and operational efficiency) which is currently being carried out under the EU Framework 6 Aerospace programme. E-CAB aims at making air travel a more pleasant experience by suggesting solutions both on the ground and on-board the aircraft. On-board solutions should provide control over the means by which the passengers can access their connectivity, with options ranging from mobile phones, PDAs, laptop computers up to new IFE interfaces.

A typical configuration of the Airbus A340-600 was used to study the effect of having multiple UMTS Node Bs installed within an aircraft. Previous work [1-2] have considered using one Node B to cover the entire cabin. While this provides a solution, this architecture requires a high transmitting power exposing the passengers seated in the vicinity of the Node B to unnecessary radiation levels. These high power levels will also cause interference with the aircraft's communication and instrumentation systems. A better solution would be to implement a number of Node Bs, placed at different locations within the fuselage, each transmitting at a lower power thus minimizing the impact of this technology on both passengers and aircraft.

In order to determine the optimum location of the Node Bs a model of the radio propagation inside the aircraft had to be developed. The three-dimensional ray tracing method which is based on geometric optics (GO) has been found to provide an adequate representation of the radio propagation map in previous studies [3-4] and was therefore used in this work. Results have shown that four Node Bs can provide optimum coverage of the cabin with transmit powers in the -10dBm range. This reduces the interference with the aircraft equipment by 50 dB with respect to a single Node B reducing safety concerns considerably.

2. UMTS PROPAGATION MODEL

The geometry of the cabin and the high density of obstacles inside a typical commercial aircraft imply severe wireless propagation conditions. With the rapid advancement in computer simulation capabilities, ray tracing techniques offer an adequate representation of the propagation characteristics inside these environments [3].

The method used is based on geometric optics (GO) and is often called brute-force ray tracing or ray launching technique. Rays are launched from a transmitter at a defined power and an estimate of the power levels along the path is found. The rays transmitted will be reflected, refracted and diffracted by the structure of the cabin and the furniture inside the cabin providing a three-dimensional map of the power levels inside the cabin. These power levels provide an estimate of the field strength that would be perceived by a mobile station at any location within the cabin.

Ray Tracing

In the cabin scenario, the UMTS signal wavelength is much smaller than the dimensions of the environment implying that the approximation of the GO hypothesis holds and ray tracing can be used. Under GO assumptions, the propagation can be modeled as rays. By definition a ray is associated to a local plane wave which can be represented by [3]:

$$\nabla^2 \psi + k^2 n^2 \psi = 0 \quad (1)$$

where ψ is the waveform function which governs the scalar wave propagation, n is the refraction index of the media and k is the wave number. A solution for ψ can be given as [3]:

$$\psi = A e^{-jks} \quad (2)$$

The function A determines the amplitude of the wave while the function S determines the direction and phase. Using (1) and (2) we conclude that if

$$\frac{\nabla^2 A}{A k^2} \ll n^2 \quad (3)$$

a solution which is independent of frequency can be obtained and hence GO can be used.

Rays passing through the medium will experience reflection, refraction and diffraction due to the presence of obstacles within their path. Due to the high complexity of the cabin environment, each obstacle is assumed to be made from homogeneous material and smooth, thus diffraction is not present. This simplifies the model as each surface can be described by its dielectric constant, magnetic permittivity and conductivity. If two media having different conductivity and permittivity are assumed to be separated by an infinite plane, then equations relating the reflected electromagnetic wave with the incident wave and the properties of the media can be obtained.

Polarization effects are taken into account by splitting the electric field into a parallel component and a perpendicular component to the incident surface. The reflected and refracted rays can be estimated by taking the product of each component with the corresponding Fresnel's coefficient and are given by [5]:

$$R_{\perp} = \frac{\cos \theta - \sqrt{\hat{\epsilon}_r - \sin^2 \theta}}{\cos \theta + \sqrt{\hat{\epsilon}_r - \sin^2 \theta}} \quad (4)$$

$$R_{\parallel} = \frac{\hat{\epsilon}_r \cos \theta - \sqrt{\hat{\epsilon}_r - \sin^2 \theta}}{\hat{\epsilon}_r \cos \theta + \sqrt{\hat{\epsilon}_r - \sin^2 \theta}} \quad (5)$$

$$T_{\perp} = \frac{2 \cos \theta}{\hat{\epsilon}_r \cos \theta + \sqrt{\hat{\epsilon}_r - \sin^2 \theta}} \quad (6)$$

$$T_{\parallel} = \frac{2\sqrt{\hat{\epsilon}_r} \sin \theta}{\hat{\epsilon}_r \cos \theta + \sqrt{\hat{\epsilon}_r - \sin^2 \theta}} \quad (7)$$

where θ is the angle of incidence, and $\hat{\epsilon}_r = \epsilon_r - j(\eta/2\pi)\sigma\lambda$ is the relative complex dielectric constant with ϵ_r being the relative dielectric constant, σ being the conductivity of the materials, λ the wavelength in meters, R being the reflection coefficients, and T being the refraction coefficients. These relations are valid if the dielectric constant of air is ϵ_0 [3].

Signal Strength Propagation Map

The A340-600 cabin was modeled using a typical setup, this included, the fuselage and the seats. The signal strength propagation map was determined by placing the Node Bs at fixed locations inside the cabin and launching the rays from each transmitter. At each point inside the cabin the rays passing through that point are added to estimate the signal strength at that point. Thus a propagation map is created indicating the radio coverage for each solution.

A ray emanating from a transmitter travels in free space until it hits a surface where it is reflected or refracted and reflected as shown in Figure 1. After this interaction the one or two rays that result after the main ray hits the surface are sent again. This process is repeated until the ray's power is below a certain threshold.

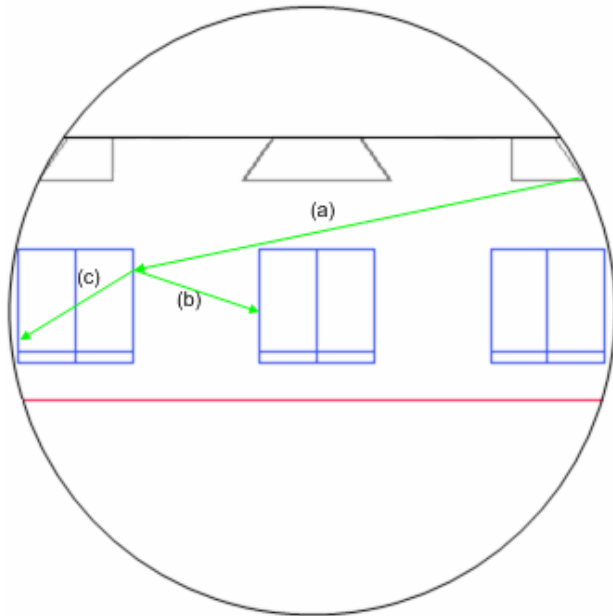


Figure 1 – Ray tracing inside the cabin (a) main ray leaving transmitter, (b) reflected ray and (c) refracted ray.

The power received by the path of the k^{th} ray arriving at a single point is given by [3]:

$$P_k = P_T \left(\frac{\lambda}{4\pi r} \right)^2 G_T G_R \prod_i \rho_i \prod_j \tau_j \quad (8)$$

where P_T is the transmit power in Watts, G_T and G_R are the transmitter and receiver gains respectively, λ is the wavelength in meters, r is the total unfolded path length in meters, ρ_i and τ_j are the reflection and refraction coefficients respectively as determined from (4) – (6), and i and j are the indexes that increment over reflection and refraction respectively.

To simplify the polarization model some assumptions were made based on [6]. The phase of the received field ϕ_k is calculated for fast fading prediction, with ϕ_k being a function of the unfolded path length and the number of reflections. Therefore the signal strength at a point can be calculated using:

$$P_R = \left| \sum_k \sqrt{P_k} e^{-j\phi_k} \right|^2 \quad (9)$$

and

$$\phi_k = kr + R_{sh} \quad (10)$$

where k is the wavenumber (m^{-1}), r is the length of the path in meters, and R_{sh} is the phase shift due to reflection in radians.

Model for Reflection

Reflection was implemented according to Fermat's principle, where the direction of the reflected ray is given by:

$$\vec{r} = \vec{v} - 2(\vec{n} \cdot \vec{v})\vec{n} \quad (11)$$

where \vec{r} is the incident ray, \vec{v} is the normal to the plane of incidence, and \cdot is the dot product operator. Reflections inside the cabin will occur on every surface. Since in this scenario the wavelength is much smaller than the obstacle, the surfaces of all the obstacles within the cabin can be considered as smooth and planar. This simplifies the model by eliminating the edges and allowing Fresnel coefficients to be used. Using Fresnel coefficients, the electric field will suffer a phase shift of π radians after each reflection. The reflected field power becomes:

$$P_r = \sqrt{P_{r\parallel}^2 + P_{r\perp}^2} \quad (12)$$

where

$$P_{r\parallel} = P_{i\parallel} \cdot |r_{\parallel}|^2 \quad (13)$$

$$P_{r\perp} = P_{i\perp} \cdot |r_{\perp}|^2 \quad (14)$$

$$P_{i\parallel} = P_i \cos \theta \quad (15)$$

and
$$P_{i\perp} = P_i \sin \theta \quad (16)$$

The subscripts i and r represent the incident and reflected rays respectively, while r_{\parallel} and r_{\perp} are calculated using (4) and (5) respectively.

The GO principle can also be applied to the curved cabin walls since the radius of curvature of this surface is large compared to the wavelength of the UMTS signal. Thus the incident ray is reflected at the tangential plane of the surface at the point of intersection between the incident ray and the cabin wall.

Model for Refraction

Refraction will occur whenever a ray hits an obstacle. In our model the signals that are refracted within the aircraft's fuselage are assumed to be absorbed within the material and will not travel outside the aircraft. The direction of the refracted ray can be estimated using [3]:

$$\vec{t} = n\vec{v} - \left(n(\vec{v}, \vec{n}) + \sqrt{1 - n^2(1 - (\vec{v}, \vec{n})^2)} \right) \vec{n} \quad (17)$$

where $n = n_1/n_2$ and n_1 and n_2 are the refraction indexes of the two media.

The refracted power can be calculated using:

$$P_t = \sqrt{P_{t\parallel}^2 + P_{t\perp}^2} \quad (18)$$

where

$$P_{t\parallel} = P_{i\parallel} \cdot |t_{\parallel}|^2 \quad (19)$$

$$P_{t\perp} = P_{i\perp} \cdot |t_{\perp}|^2 \quad (20)$$

where the subscripts i and t represent the incident and refracted rays respectively, t_{\parallel} and t_{\perp} are calculated using (6) and (7) respectively, and $P_{i\parallel}$ and $P_{i\perp}$ are found through (15) and (16). The model assumes that the obstacles present a constant dielectric and thus the refracted ray will not incur a phase shift.

Model of the Cabin

A three-dimensional model of the Airbus A340-600 was used as the simulation environment. The structure of the aircraft was modeled by using a circular cylinder to represent the fuselage, a horizontal plane to model the floor, and other planes representing the ceiling and the stowage bins, as shown in Figure 2. The galleys which separate the different class sections within the cabin are not shown in this figure.

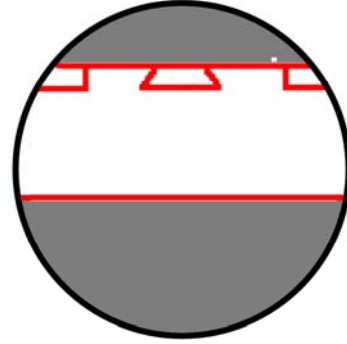


Figure 2 – Cross-section of the A340-600 without seats.

Seats having a certain thickness are then fitted inside the model as shown in Figure 3. Seats are modeled as two intersecting planes having a certain dielectric constant, magnetic permittivity and conductivity. To simplify the model the armrests were not considered.

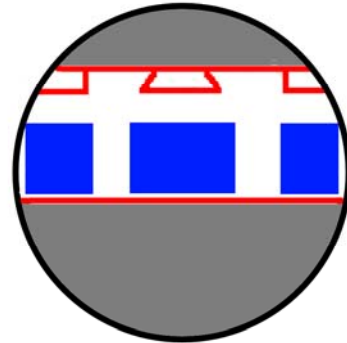


Figure 3 – Cross-section of the A340-600 with seats.

Model of the Node B

Each Node B station is equipped with an omni-directional antenna. Hence it can be modeled as a point source radiating rays uniformly in the three-dimensional space. The Monte Carlo stochastic ray launching model was used to model each transmitter [3]. This generates rays in random directions within the cabin having equal probability.

The one-dimensional probability density functions in the spherical coordinates ϕ , where $0 \leq \phi \leq 2\pi$, and θ , where $0 \leq \theta \leq \pi$, are given by [3]:

$$p_{\theta}(\theta) = \int_0^{2\pi} p_{\theta,\phi}(\theta, \phi) d\phi = \frac{\sin \theta}{2} \quad (21)$$

$$p_{\phi}(\phi) = \int_0^{\pi} p_{\theta,\phi}(\theta, \phi) d\theta = \frac{1}{2\pi} \quad (22)$$

These two randomly distributed variables are generated using:

$$\theta = \arccos(1 - 2\xi_1) \quad (23)$$

and

$$\phi = 2\pi\xi_2 \quad (24)$$

where ξ_1 and ξ_2 are random variables uniformly distributed in $[0,1]$ and in $[0,1]$ respectively.

The signal strength model

The complexity of the simulation depends on the number of rays that are launched from each Node B. If the angle between any two rays is too small then both rays will represent the same electromagnetic plane wave. On the other hand, if the angle between them is too large some signal strength contributions might be lost. Hence a compromise must be found between computational complexity and accuracy. Once the rays are launched from each transmitter, the power at each point inside the cabin is calculated using equation (9) hence creating a signal strength propagation map.

3. SIMULATION RESULTS

A model of a typical configuration of the Airbus A340-600 was developed using Autocad[®] and imported into Matlab[®]. The ray launching technique described above was also implemented in Matlab[®]. Various authors have implemented only one Node B [1-2] to cover the entire cabin and thus this case was investigated first. Through simulation, the optimum power required by the transmitting Node B placed at the center of the aircraft was found to be 40 dBm. With this power the passengers at the first and last rows receive the minimum signal strength defined by the UMTS standard, that is -120 dBm. This means that the mobile devices at these extremes are transmitting at maximum power possibly interfering with the aircraft's signals. The same effect occurs at the Node B which is transmitting at high power. The radio coverage map for this scenario is shown in Figure 4 where the low reception at the front seats can be noticed.

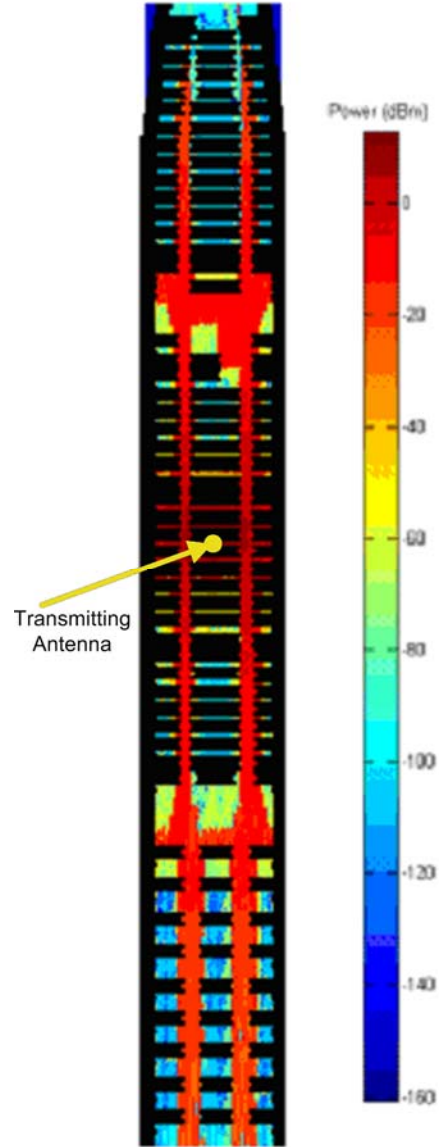


Figure 4 – Top view radio coverage map with 1 Node B.

Increasing the number of Node Bs helps in obtaining a better coverage map while keeping the power levels low. The simulation result for the radio coverage using four Node Bs each transmitting at -10dBm is shown in Figure 5. The Node Bs are transmitting in the same frequency band with the different cells being distinguished through different scrambling codes. Comparing this coverage map with the one in Figure 4, it is evident that this solution provides better coverage than the single Node B scenario and requires less transmit power from the mobile devices, since the received signal strength is never below -100dBm. Hence the interference from this network is deemed to be substantially lower. Further enhancement can be obtained by increasing the number of Node Bs however wiring problems and its corresponding weight will increase.

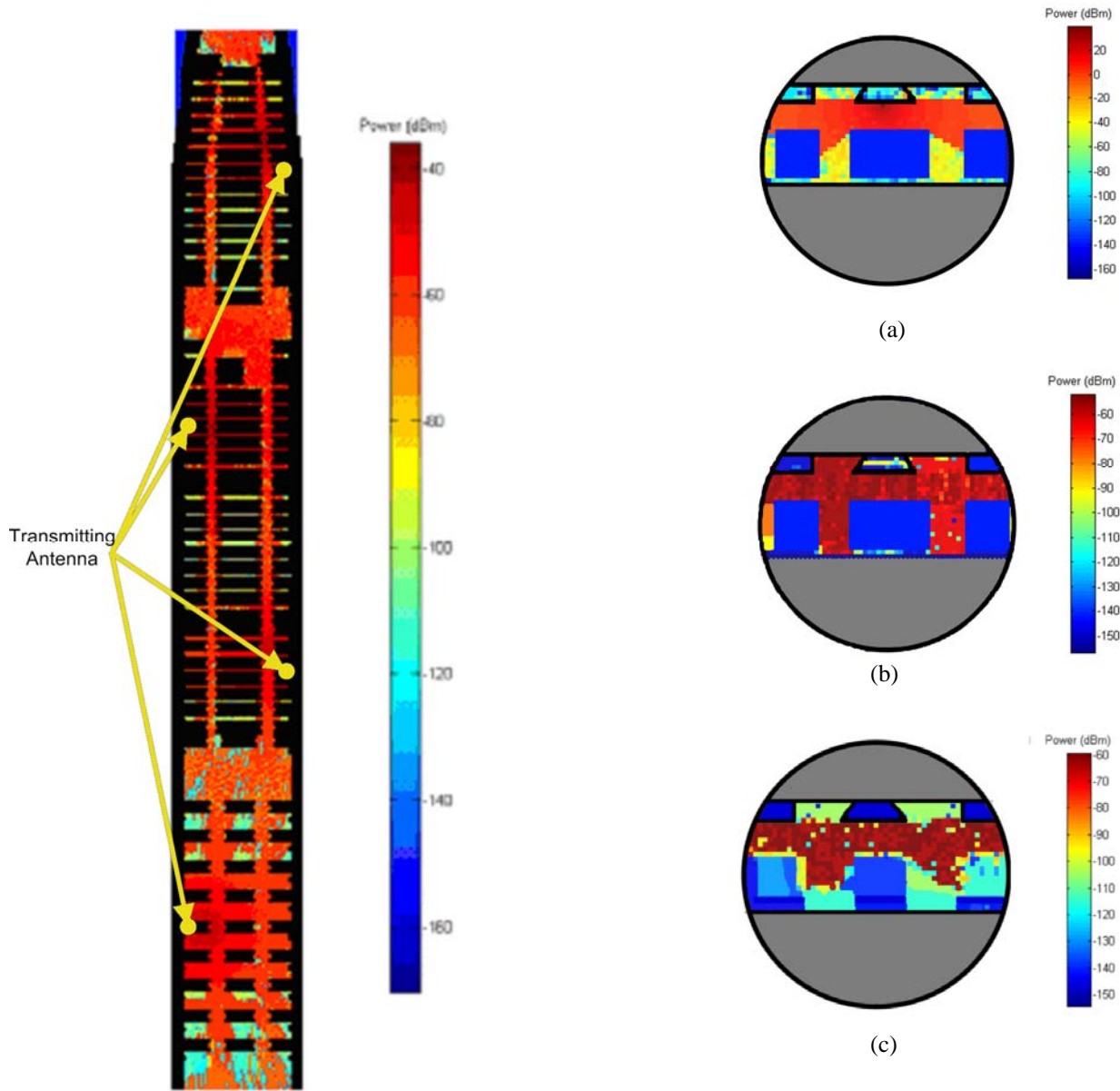


Figure 5 – Top view radio coverage map with 4 Node Bs.

4. DISCUSSION

The simulation results were compared using cross-sectional views across the A340-600. These views give a better perspective of the effective signal strengths present at various locations within the cabin. From Figure 6(a) it is clear how the signal strength in the vicinity of the Node B is saturated leading to a high level of interference. This is less pronounced in Figure 6(b), where the power levels at each Node B are 50dB lower. Figures 6(c) and (d) compare the signal strength levels at the extremes of the cabin near the front seats of the aircraft. Again the gain in using more than one Node B is evident.

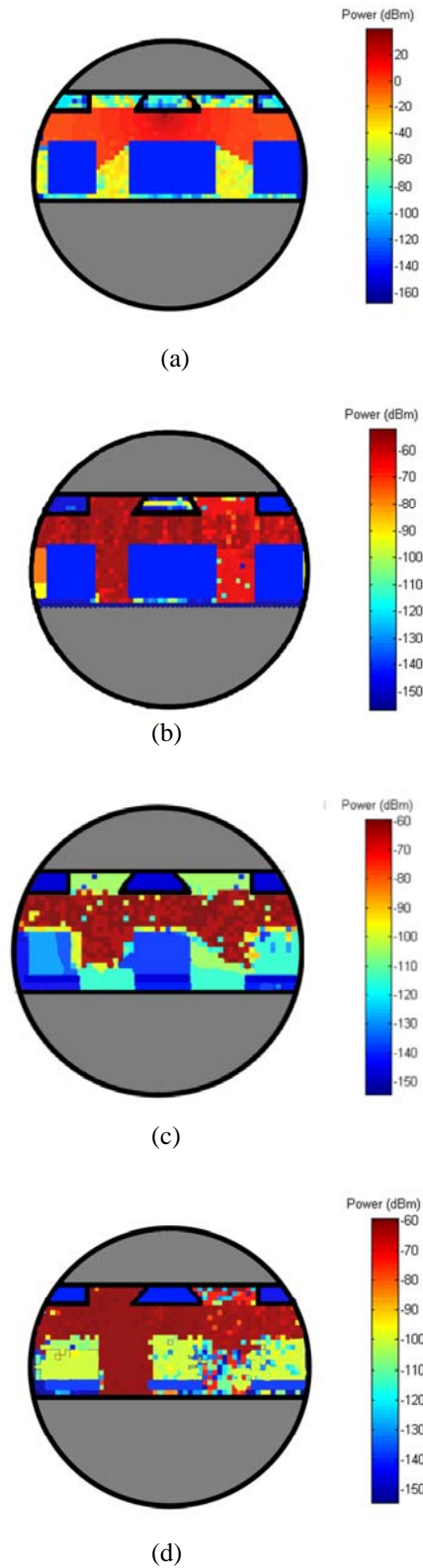


Figure 6 – Cross-sectional views (a) center of cabin with one Node B, (b) center of cabin with four Node Bs, (c) front seat of cabin with one Node B, and (d) front seat of cabin with four Node Bs.

The number of Node Bs was kept to a minimum because of the wiring required to connect the Node Bs with the switch. This connection can be done using a wireless link, however the optimum location of the antennas lies on the lower part of the stowage bins and therefore can be easily compromised by passenger movements. A possible solution is to implement this point-to-point link at a different location near the surface of the fuselage requiring only a small wiring distance.

5. CONCLUSION

A solution that optimizes network coverage within an aircraft has been presented. The ray launching technique which is based on geometric optics has been used to estimate the signal strength propagation map inside the Airbus A340-600. The model was used to estimate the optimal locations of the Node Bs within the aircraft. Simulation results have shown that a better radio coverage is obtained if four Node Bs are used instead of one. Also each Node B's transmitting power has been reduced by 50dB implying that the interference on the aircraft's electronics and communication links are also reduced drastically.

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BIOGRAPHY



Carl James Debono received his B.Eng.(Hons.) degree in Electrical Engineering from the University of Malta, Malta, in 1997 and the Ph.D. degree in Electronics and Computer Engineering from the University of Pavia, Italy, in 2000.

Between 1997 and 2001 he was employed as a Research Engineer in the area of Integrated Circuit Design with the Department of Microelectronics at the University of Malta. In 2000 he was also engaged as a Research Associate with Texas A&M University, Texas. In 2001 he was appointed Lecturer with the Department of Communications and Computer Engineering at the University of Malta and is now a Senior Lecturer. His research interests are in RF and microwave systems development and applications, and modeling of communication systems.



Reuben A. Farrugia received the first degree in Electrical Engineering from the University of Malta, Malta, in 2004.

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